A ONE MEGAJOULE ARC DISCHARGE SHOCK TUBE AS

A CHEMICAL KINETICS RESEARCH FACILITY

by

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INTRODUCTION

A shock tube driven by an arc discharge has recently been placed in operation at Ames Research Center. This shock tube is to be used for gas physics and chemical kinetics research. Consistent with this use it was designed to produce shock wave velocities as high as 12 km/sec and to obtain initial test gas pressures as low as 10μ of Hg. The shock tube has comparatively large physical dimensions, the most significant being the 6-inch internal diameter of the driver, the largest diameter arc heated driver known to the author. The pertinent physical features of the shock tube, particularly those related to the performance objectives, are described herein. The primary features of the energy storage and delivery portion of the shock tube system and the problems encountered in placing the capacitor bank in operation are discussed. A few preliminary test results obtained in checking the operation of the shock tube are also presented.

DESCRIPTION OF FACILITY

Shock Tube

The over-all arrangement of the shock tube is shown in figure 1. In designing this facility, the following three requirements were considered: (1) high shock wave velocities, of the order of 12 km/sec (mm/μsec) or greater in order to simulate planetary entry conditions; (2) capability for low driven gas pressures in order to stretch the nonequilibrium reaction zone to a resolvable length; (3) adequate testing time at these low driven gas pressures in order to study the reactions of interest.

In the following sections, the pertinent features of the shock tube will be discussed in light of meeting the performance objectives. The discussion will proceed from the driver to the driven tube, much the same as the operational chain of events.

<u>Driver</u>.- The first requirement clearly dictated the necessity for an arc heated driver gas of low molecular weight, as demonstrated in the pioneering work of references 1 and 2. A detailed drawing of the driver is shown in figure 2. The comparatively large driver diameter, a nominal 6-inch inside diameter, was selected in compromise to the following considerations:

(1) It was desired to have a nonoscillatory arc discharge in the driver. This criterion stipulates that the RC time constant of the circuit must be a certain value. On this basis, and since the resistance of the driver is inversely proportional to its area, calculations were made which indicated that a driver diameter as large as about 6 inches could be used with a good certainty of a nonoscillatory discharge.

(2) It was believed that the driven tube to driver area ratio should be small (for arc discharge shock tubes, the usual practice is for the area ratio, $A_{\text{driven tube}}/A_{\text{driver}}$, to be greater than 1.0). Since the amount of energy required to produce a given shock wave increases with area ratio, the choice of a small area ratio, say for example 4.0, would make for much more efficient use of the capacitor bank energy. (For example, normalizing the energy required, Q, to an area ratio of 1, would give $Q = 2$ for an area ratio of 4, and $Q = 10$ for an area ratio of 20.) It was also believed, and more intuitively than the above considerations, that the transition from the driver to driven tube without perturbing the interface and decreasing the available testing time would be more favorable with a smaller area ratio.

(3) It was known for reasons described in the next section that the driven tube diameter would have to be about 12 inches.

With the above considerations in mind, it was decided to make the driver diameter as large as possible, and a nominal diameter of 6 inches was selected.

The length of an arc heated driver of this type must be as short as possible so that the maximum driver gas temperature (sound speed) is attained with a given amount of energy input. However, a minimum length is stipulated by the criterion that the rarefaction wave, generated by the diaphragm opening, and reflected from the rear of the driver, does not catch up with the test gas. The required driver length is therefore inversely proportional to shock wave velocity. With this in mind, provision was made for varying the internal length of the driver up to 2 feet.

Figure 3 is a photograph of the driver. The collector rings and electrical cables, to be described later, are seen at the end of the driver. The teflon liner, which prevents the arc from striking the walls of the driver, consists of two 1/8-inch sheets, rolled and pressed into the driver chamber. The seams of the sheets are staggered 180° to provide adequate electrical insulation. The driver is fabricated with a modified 18-8 stainless steel having a very low permeability.

Diaphragm and transition section. - The shock wave stabilizing section and the diverging section accomplish the transition from the 6-inch diameter of the driver to the 12-inch diameter of the driven tube. The diaphragms are held at the upstream end of the shock wave stabilizing section. A provision has been incorporated which allows the diaphragms to be mounted and the driven tube in turn evacuated independently of the driver being coupled to the diaphragm section.

Flat scored diaphragms, as shown in figure 4, are used. They are scored to various depths to control their bursting pressure. The scoring is accomplished with an end mill which cuts a 90° included angle groove. The diaphragms, which are fabricated of an 18-8 stainless steel, rupture into a square section, shown in figure 5. The recesses for the diaphragm petals to fold into upon rupturing are clearly seen in figure 5. The square cross section was chosen, as opposed to a circular cross section, to minimize the risk of losing petals. The square portion of the diaphragm section transforms smoothly into the 6-inch-diameter circular configuration of the driven tube's shock wave stabilizing section.

The purpose of the shock wave stabilizing section was to allow the shock wave to become at least partially formed before entering the diverging section. The equivalent conical diffusion angle of the diverging section defined as

$$\alpha \equiv \tan^{-1} \frac{\text{(Maximum diameter)} - \text{(Minimum diameter)}}{\text{Length of section}}$$

was held at 12° to minimize shock wave perturbation of the interface. The entrance and exit portions of the diverging section were faired with a radius of curvature equal to the local diameter. The diffusion angle and shape of the entrance and exit fairing were believed to be particularly important since the strength and curvature of the oblique shock waves that stand at the exit, as well as the possibility of having a normal shock wave at the focal point of the oblique shock waves, are increased with large diffusion angles and sharp corners.

Driven tube.- The second and third requirements, defined earlier in this section, are concerned mainly with the driven tube. An overall view of the driven tube was given in figure 1 and a photograph is presented in figure 6.

The second requirement stipulates material, internal finish, and vacuum pumping for the driven tube. Consistent with good vacuum practice, type 304 stainless steel tubing was used and this was honed to an interior finish of at least RMS 16. Vacuum pumping capacity adequate to obtain an ultimate pressure at least two orders of magnitude lower than the lowest anticipated initial driven tube pressure was incorporated (ultimate vacuum of 10^{-5} mm of Hg is obtainable in the driven tube).

The third requirement sets the size of the driven tube. The behavior of the interface between the driven and driver gas is not ideal in any shock tube, but this behavior is particularly non-ideal at the low gas densities required for chemical kinetics research. At these conditions, the interface is far from being a planar surface, behaving, in fact, similarly to the leaky piston which travels at a velocity greater than its ideal velocity and thereby decreases the length of the useful slug of gas between the shock wave and the interface. The result is a decrease of testing time. The useful testing time is increased by increasing the driven tube length until the interface and the shock wave are travelling at the same velocity. Then the slug of test gas becomes a fixed length, and no further increase in testing time is realized with increased length. This phenomenon governs the practical length of this type of shock tube. Testing time is also increased by increasing the diameter of the driven tube and it will change in proportion to the square of the diameter.

The 12-inch diameter was chosen because it appeared that it would provide a testing time adequate for the needs of the research. (A minimum testing time of 10 μsec was necessary.) The over-all length of 32-1/2 feet from the diaphragm to the center of the test section was selected since it was long enough to give nearly maximum testing time, yet not long enough to be physically cumbersome.

Electrical Components

On the basis of parametric calculations of the energy input into the driver that is required to produce shock waves with a velocity of 12 km/sec an energy storage of 1×10^6 J in the capacitor bank was selected. A survey of experimental information on the voltage necessary to produce an arc of a given length indicated that approximately 7.5 kV/ft were needed. In order to provide an adequate operating margin for a 2-foot driver length, a voltage of 20 kV was selected for the capacitor bank.

Capacitor bank.- The 1 MJ bank contains a total of 208 capacitors, each rated for 20 kV and having a nominal capacitance of 24 μF. The bank is divided into four segments so that the energy input into the driver can be varied in units of 250,000 J at full rated voltage or at any intermediate value by varying the charge voltage. Within each segment there are 4 rows of 13 capacitors and each row of 13 is bused together in parallel. A schematic diagram of one row is shown in figure 7. Thirteen coaxial cables connect each high voltage bus to the collector ring on the driver. Each capacitor has an expulsion type fuse between its high voltage terminal and the common high voltage bus. It is necessary to bus the capacitors together in groups of 13 to insure that there is, immediately available, sufficient energy to actuate a fuse (approximately 10 to 15 kJ) before the rest of the bank can discharge into a faulty capacitor. A photograph of the physical arrangement of the bank showing fuses and charging resistors (tubes at the bottom of photograph) is given in figure 8. The vertical partitions shown between the fuses are necessary to prevent the plasma flare from an exploding fuse from shorting out the adjacent fuse.

Several problems have been encountered in the initial operation of the capacitor bank. Failures of capacitors have occurred in situations wherein it was necessary that a fuse isolate the faulty capacitor in order to prevent the energy in the rest of the bank from being discharged into that faulty capacitor. However, on two occasions, the fuses have failed to function properly. The cause of the first fuse failure appeared to be a plasma leak from the fuse case which shorted the high voltage bus and the ground bushing of the capacitor. The cause of the second fuse failure has not been determined.

The capacitors used in this bank are not rated for voltage reversal. They are rated for, what is comparatively speaking, a short life; in this case 500 hours of electrification. They are designed to operate at a high static dielectric stress of 2500 V/mil, based on dielectric pad thickness. Since for the most part similar capacitors with a high static dielectric stress have not been used extensively throughout the country, the only safeguard for insuring that problems are not encountered is to submit the capacitors to a thorough testing program before installation. Accordingly the following testing program is being initiated for the capacitors of this bank:

(1) All capacitors shall be submitted to the following tests at the factory: (a) high voltage dielectric test at 150 percent rated voltage (30,000 V) for 1 minute. (It has been determined that one source of capacitor failure was the dielectric damage resulting from a fabrication error.); (b) discharge tests for a total of 10 shots on each capacitor at 60,000 A peak current, 65 percent reversal, and 24 kc discharge frequency. (The capacitors are rated for 25,000 A, nonoscillatory peak current discharge.)

(2) Upon receipt of the capacitors at the site, the following tests will be performed to detect transportation damage: (a) high voltage dielectric test at 125 percent rated voltage (25,000 V) for 1 minute; (b) discharge test for a total of 10 shots on each capacitor at 25,000 A, critically damped.

After the capacitors are installed in the racks, the entire bank will be charged to rated voltage and discharged a sufficient number of times to prove that the capacitor bank is fully operational. During these tests, the capacitors will be bused together only through their charging resistors.

Collector rings.- The energy from each of the four segments of the capacitor bank is fed to the rear electrode of the driver through a coaxial collector ring. One of the four coaxial collector rings is shown in figure 9. The outer ring is the ground terminal and the inner ring is the high voltage collector. The inner and outer rings are connected by a micarta insulator. Each collector ring is separately removable from the driver and is attached to a grounded plate when its particular segment of the capacitor bank is not in use.

Arc initiator.- The arc is initiated with an exploding wire, similar in arrangement to that described in reference 2. In the prefire condition, the wire is held away from the rear electrode by a nylon rod. Upon firing, a solenoid releases the spring-loaded rod and the wire is drawn back until an arc is established between the wire and the rear electrode. A simple yoke of the same wire, 0.010-inch-diameter aluminum, provides the support at the front electrode.

Current viewing shunt.- In order to determine the electrical efficiency of the driver, it is necessary to know the current in the arc discharge. The shunt for making these measurements (fig. 2) is an integral part of the driver and measures the total current in the discharge at one time as opposed to the usual technique of measuring the current in a few cables. The current is determined from the voltage drop across the shunt which is measured through separate leads attached at each end of the shunt. The shunt is fabricated of 1/8-inch-thick type 330 stainless steel. Resistance of the shunt was measured with a compensated Kelvin bridge. The error in shunt signal due to the inductance of the shunt and leads has been calculated to be no more than 1 percent of the total signal. Thus, the current in the arc can be measured to good accuracy.

Safety Features

The entire capacitor bank and driver are housed in a protective room. The inside of the room is lined with 1/8-inch steel sheet, and the outside is covered with 1-1/2 inches of plywood. This has proved adequate for stopping shrapnel from the explosion resulting from a capacitor failure wherein 600,000 J was discharged into a faulty capacitor. The protective room is vacated and locked before either the driver or the capacitor bank is charged. Before the capacitor bank can be charged, a series interlock chain encompassing protective room door locks, driver charging valves, driven tube charging and evacuation valves, and driver arming must indicate that it is safe to proceed. After the bank has been charged, the protective room door locks cannot be opened unless the bank voltage is less than 20 V. A motor driven bank grounding switch is situated so as to be clearly visible to all personnel entering the protective room and to indicate that the bank is grounded.

PRELIMINARY PERFORMANCE

Some performance data have been obtained in the process of checking the operation of the shock tube. These data are solely concerned with the shock tube itself and do not represent research data. All of the testing has been with air as the driven gas.

To assess the performance of a shock tube of this type, it is important to know the electrical efficiency of the discharge process. The energy actually dissipated in the discharge process is:

$$W = \int_0^\infty E(t)I(t)dt$$

and the electrical efficiency is then defined as

$$\eta_E = \frac{2W}{CE^2}$$

where C is bank capacitance, E is bank voltage, and I is discharge current. The time dependent voltage and current are obtained from oscilloscope records as shown in figure 10. The electrical efficiencies obtained in this manner are between 70 and 80 percent which are lower than the 90 to 95 percent values of reference 2. The reason for these low values has not been determined.

The primary measure of the efficiency of an arc discharge shock tube is defined by its ability to produce a certain shock wave velocity from the energy discharged into the driver. The ideal energy density required to produce a shock wave of a given velocity is shown in figure 11. These curves were calculated from those of reference 2 and are plotted for a constant initial pressure of 10^{-4} atmosphere of air in the driven tube, and for various initial pressures in the driver. Also plotted in this figure are several experimental points that have been obtained in the preliminary tests. The experimental points have been obtained with the internal length of the driver set at 12 inches which gives a volume of 5105 cm^3. The low energy densities are due to limiting the capacitor bank voltage to 10 kV until the testing program discussed earlier had been completed and that only 156 capacitors (3750 μF) were available. Extrapolation of the performance obtained with energy densities in the range of 26 to 37 J/cm^3 to the value of 195 J/cm^3 obtainable with a full megajoule of energy in the capacitor bank indicates that shock wave velocities in excess of 12 km/sec should be obtained. Defining the over-all efficiency as the ideal energy density required to produce the measured shock velocity divided by the actual energy density gives:

$$\eta = \frac{(W/V)_{ideal}}{(W/V)_{action}}$$

This efficiency takes into account all possible losses such as arc losses, radiation from the driver gas, and non-ideal shock tube performance. It can be seen from figure 11 that over-all efficiencies as high as 60 percent have been obtained. This figure compares well with the 50 percent efficiency that is usually obtained with this type of shock tube.

The shock wave velocities have been measured by observing the radiation behind the shock wave with photomultipliers and by ionization gages, located at two accurately known stations. The photomultipliers had an S-5 spectral response. In order to obtain meaningful data the radiation was collimated by two 0.0015-inch slits, 1 foot apart.

Typical outputs of the photomultipliers at two different initial driven tube pressures are shown in figure 12. The initial spike in both traces is taken to be the nonequilibrium radiation from behind the shock wave. The shock wave was assumed to have arrived when the signal was 2 percent of its maximum value. The jagged signal immediately following is interpreted as the driver gas radiation. The low level of the driver gas radiation is as would be expected from the low energy densities of the testing to date. The testing times appear to be about 30 to 40 μsec or slightly greater than half the ideal value. These values are greater than those presented in reference 3 (a 6-inch-diameter driven tube) as would be expected from the larger driven tube diameter of 12 inches.

A typical output of an ionization gage is also shown in figure 12. The signal rise from these gages is much more sharply defined. The shock velocities presented in figure 11 are based on the ionization gage signal.

The pressures in the driver have been measured with a Kistler Model 601 Transducer. A small 1/8-inch hole was drilled through the liner and a 1/32-inch sheet of teflon was placed at the bottom of the hole. The face of the transducer was backed up against the 1/32-inch sheet. A typical output trace is shown in figure 13. This output has been filtered with a 50 kc filter, but there is still a significant amount of ringing. However, a rough estimate of the pressure can be made and this checks fairly well with anticipated results. The time history of driver pressure is evident.

CONCLUDING REMARKS

From the preliminary results that have been obtained, the following remarks can be made:

Preliminary evaluation indicates the achievement of fairly high over-all efficiencies. Extrapolation from the performance obtained with energy densities of less than 37 J/cm^3 to the value of 195 J/cm^3 obtainable with a full megajoule of energy in the capacitor bank indicates the shock wave velocities in excess of 12 km/sec should be obtained.

The testing times indicated appear to be quite good. This confirms the choice of a large diameter driven tube.

Problems have been encountered with capacitor and fuse failures. A testing program has been initiated to prove that the capacitor bank is operational.

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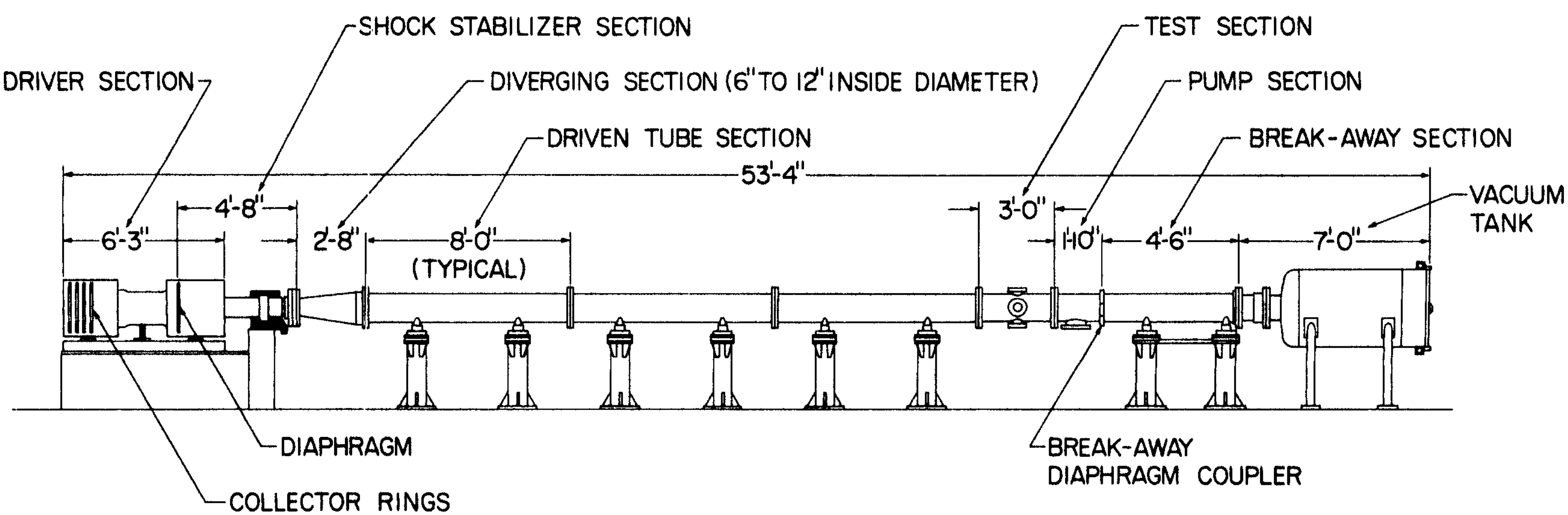

Fig. 1.- Sketch of arc discharge shock tube.

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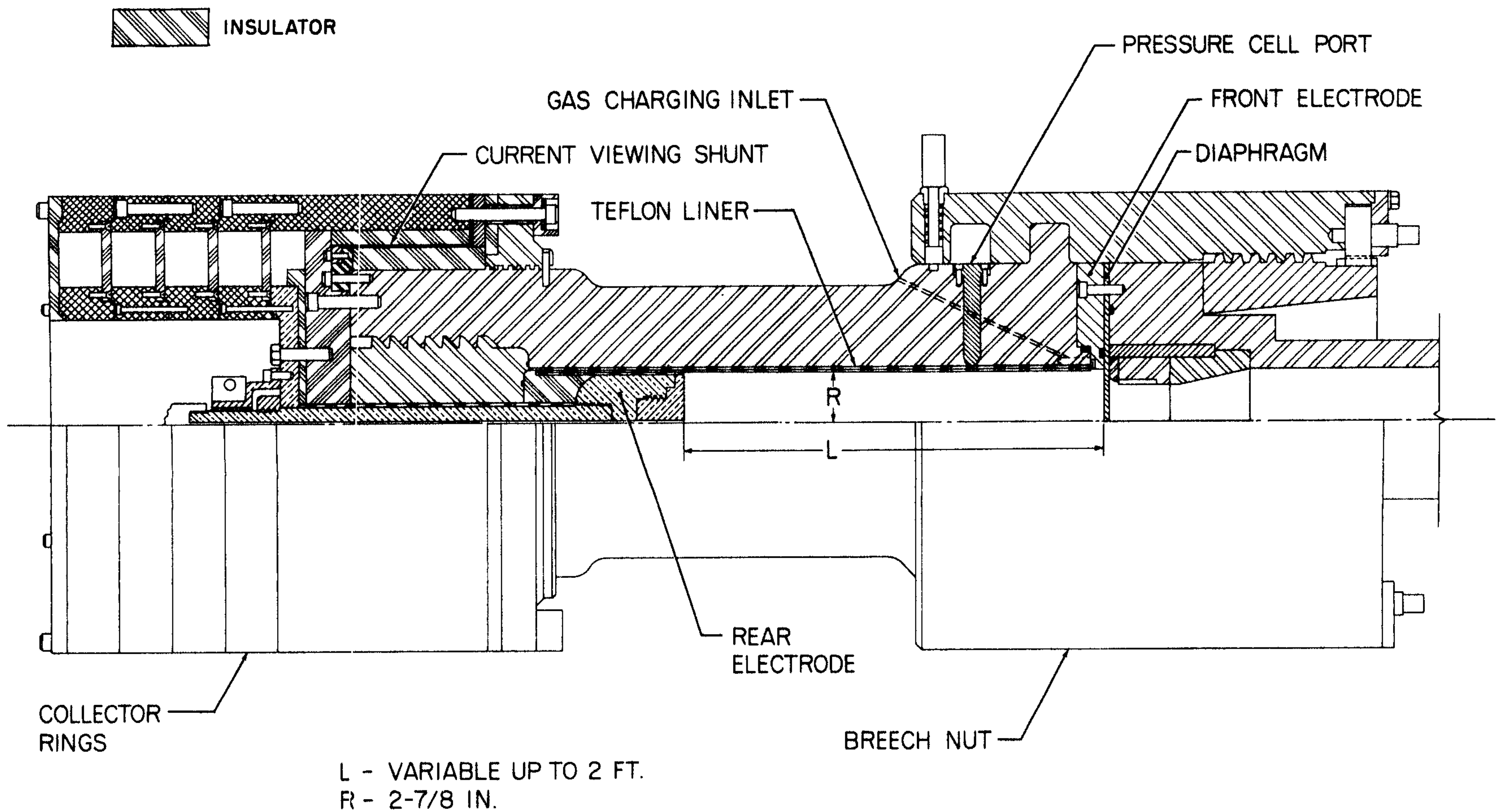

Fig. 2.- Details of arc discharge driver.

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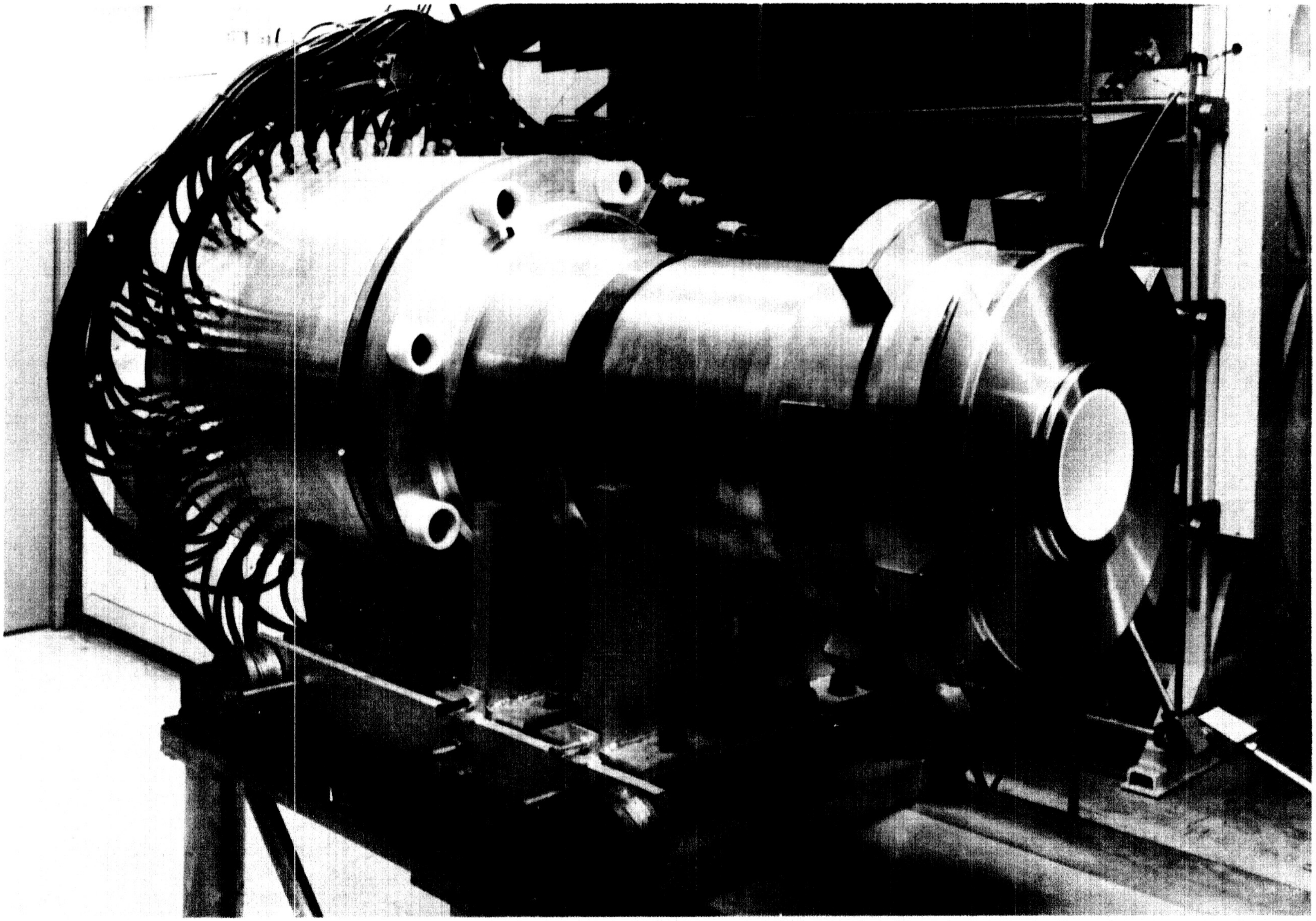

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Fig. 3.- Arc discharge driver.

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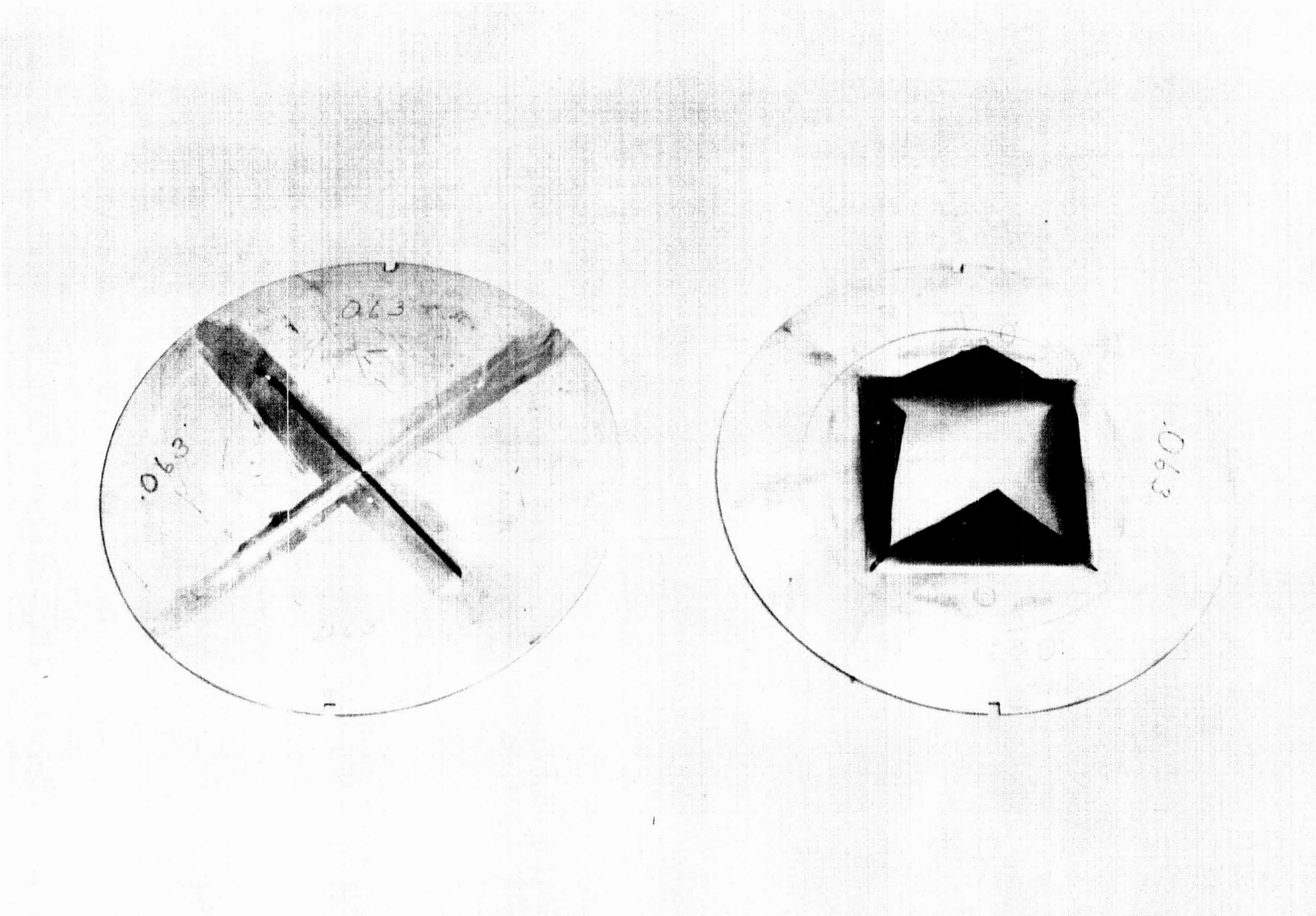

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Fig. 4.- Scribing and petaling pattern of diaphragms.

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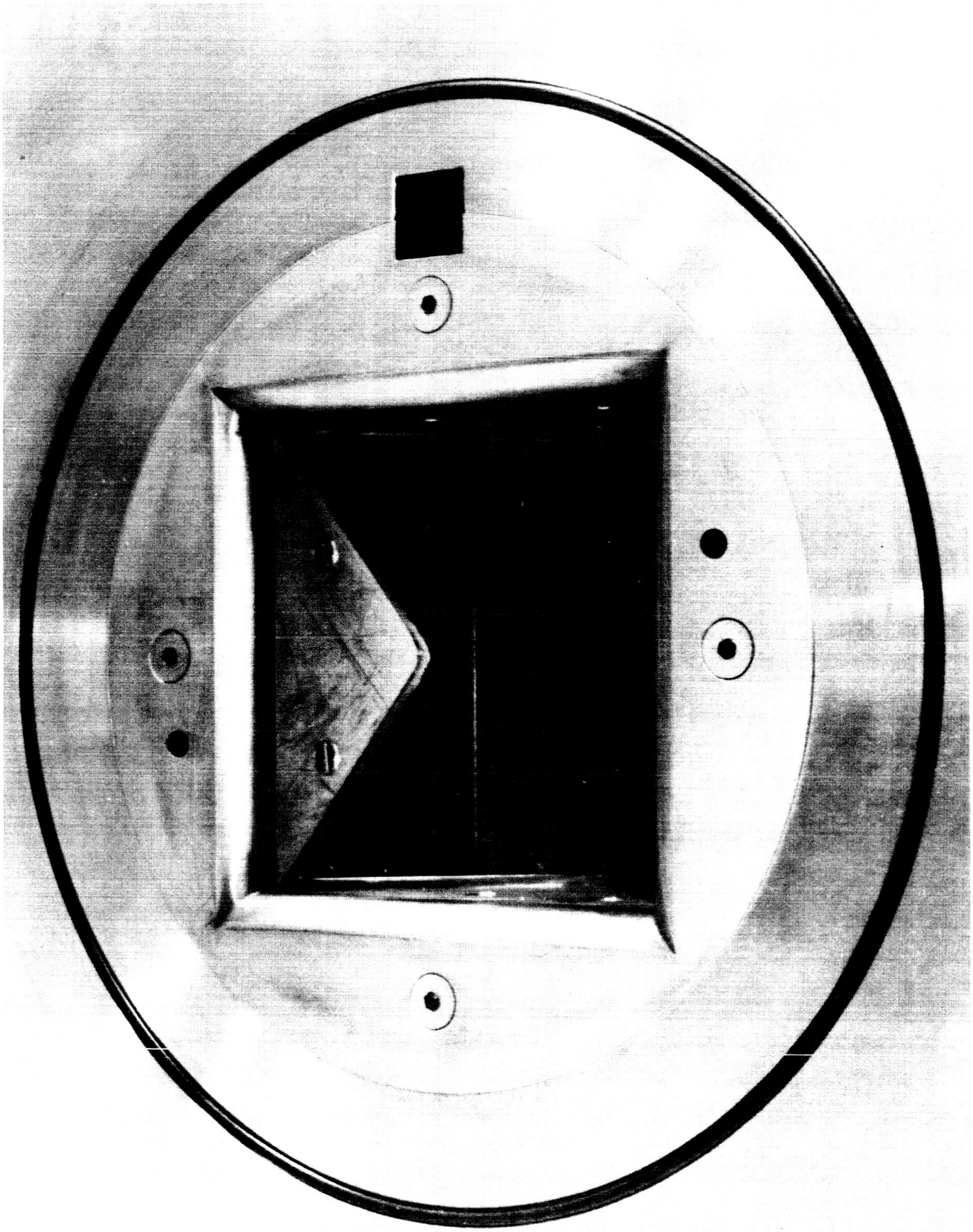

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Fig. 5.- Diaphragm holder.

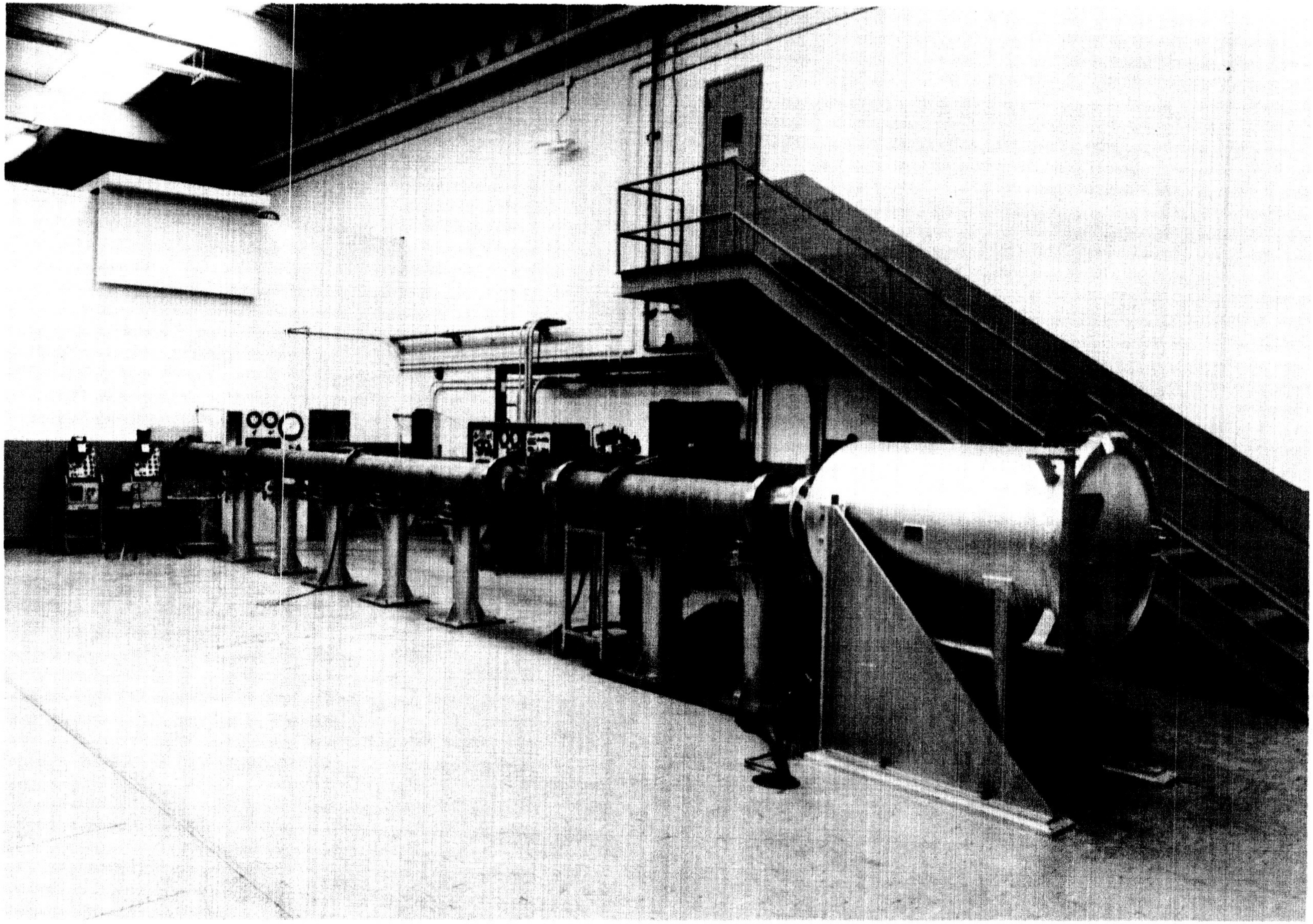

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Fig. 6.- Over-all view of driven tube.

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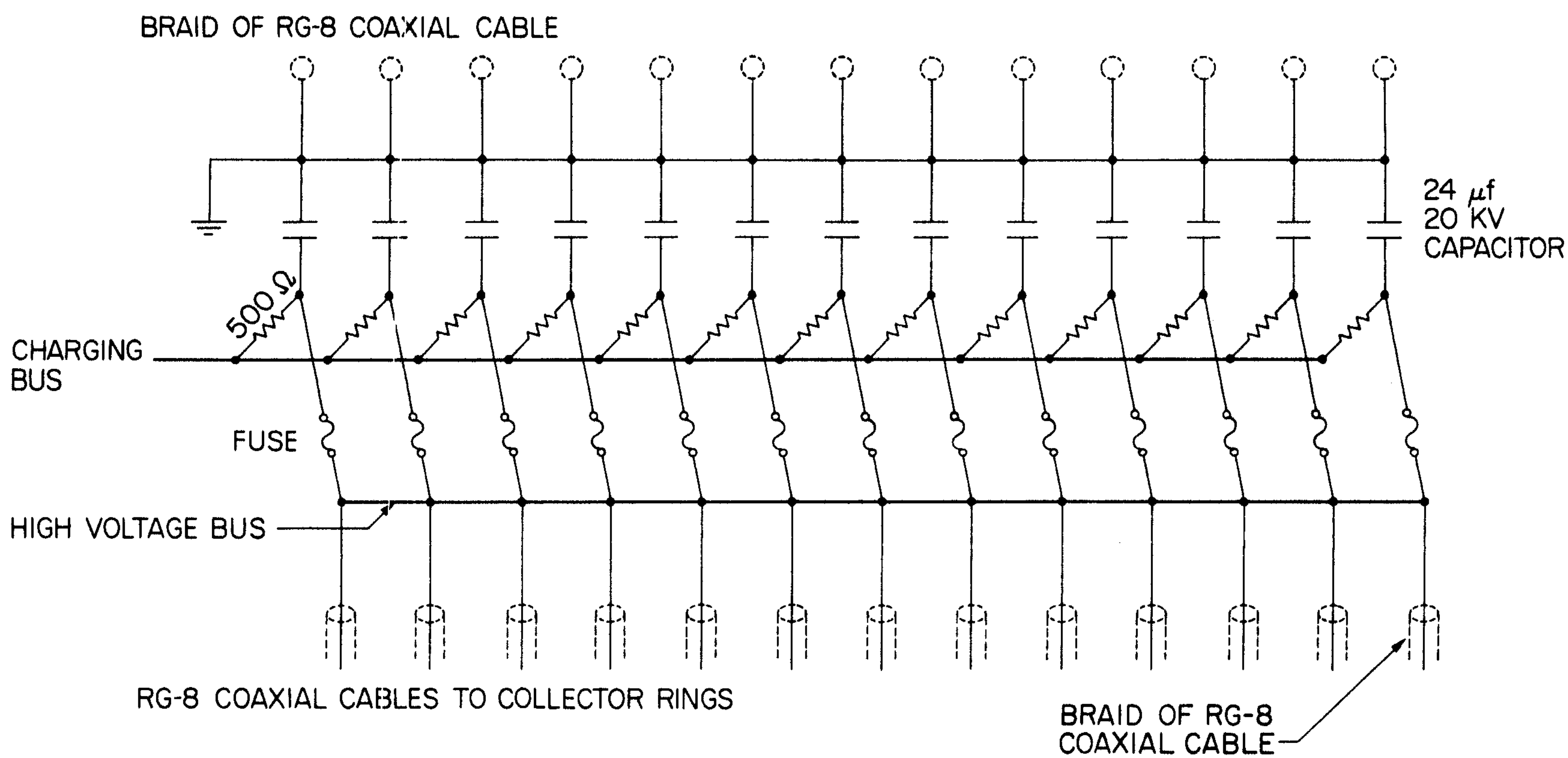

Fig. 7.- Schematic diagram of one row of capacitor bank.

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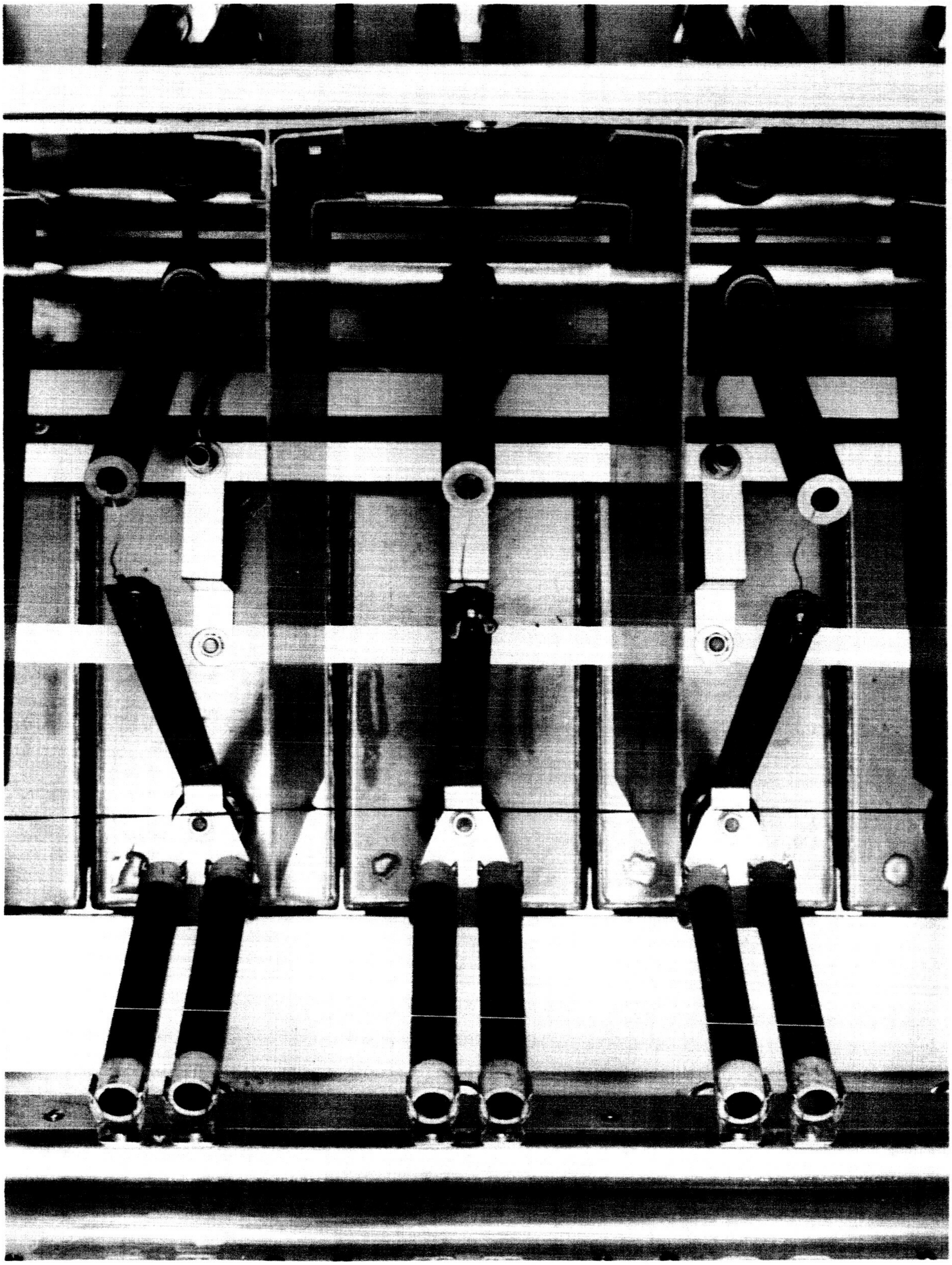

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Fig. 8.- View of capacitors, fuses, charging resistors, and related buswork.

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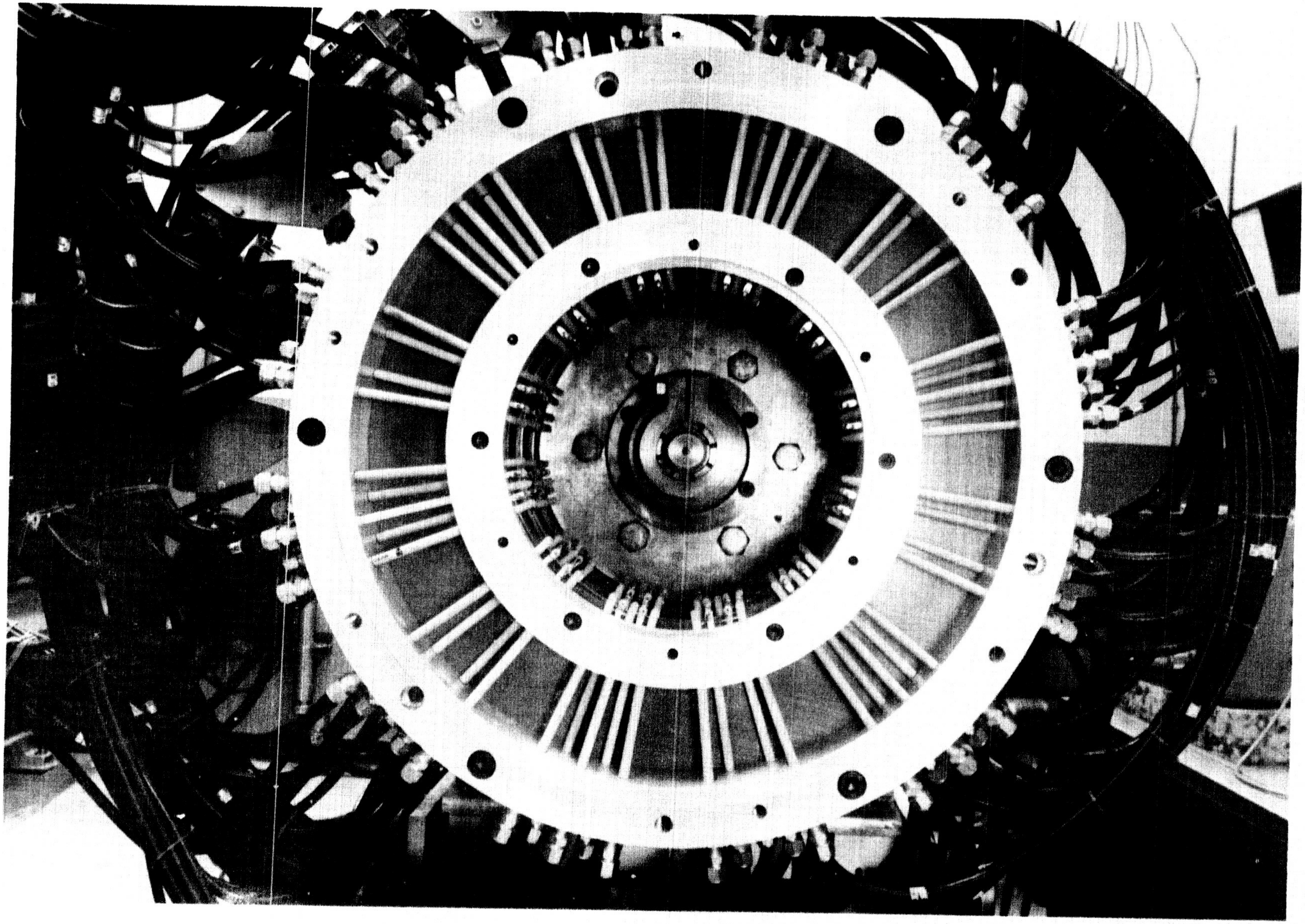

Fig. 9.- Details of collector ring.

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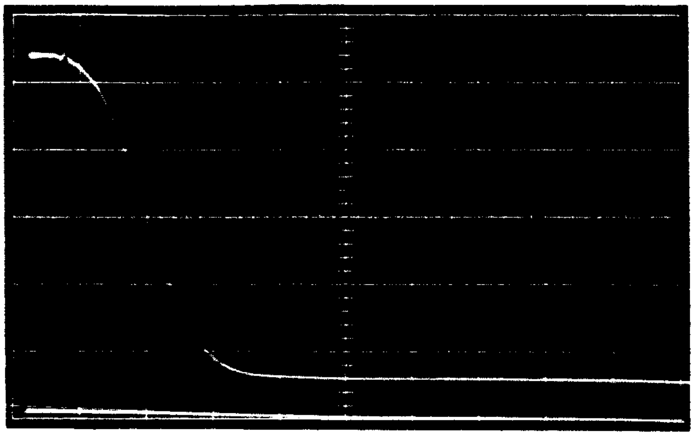
Voltage



Current

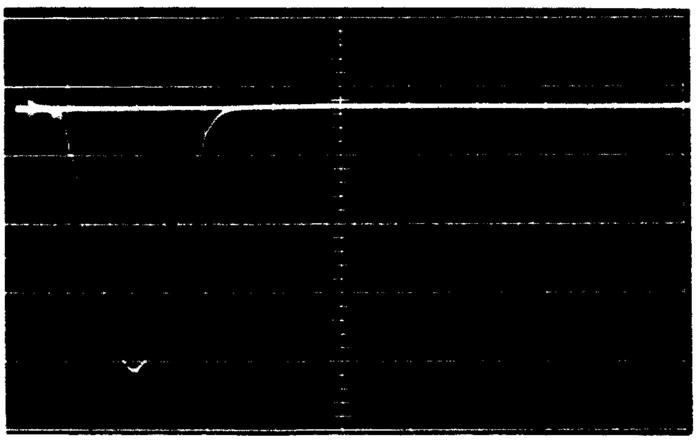


Fig. 10.- Voltage and current wave forms. Nominal voltage of 10 kv.

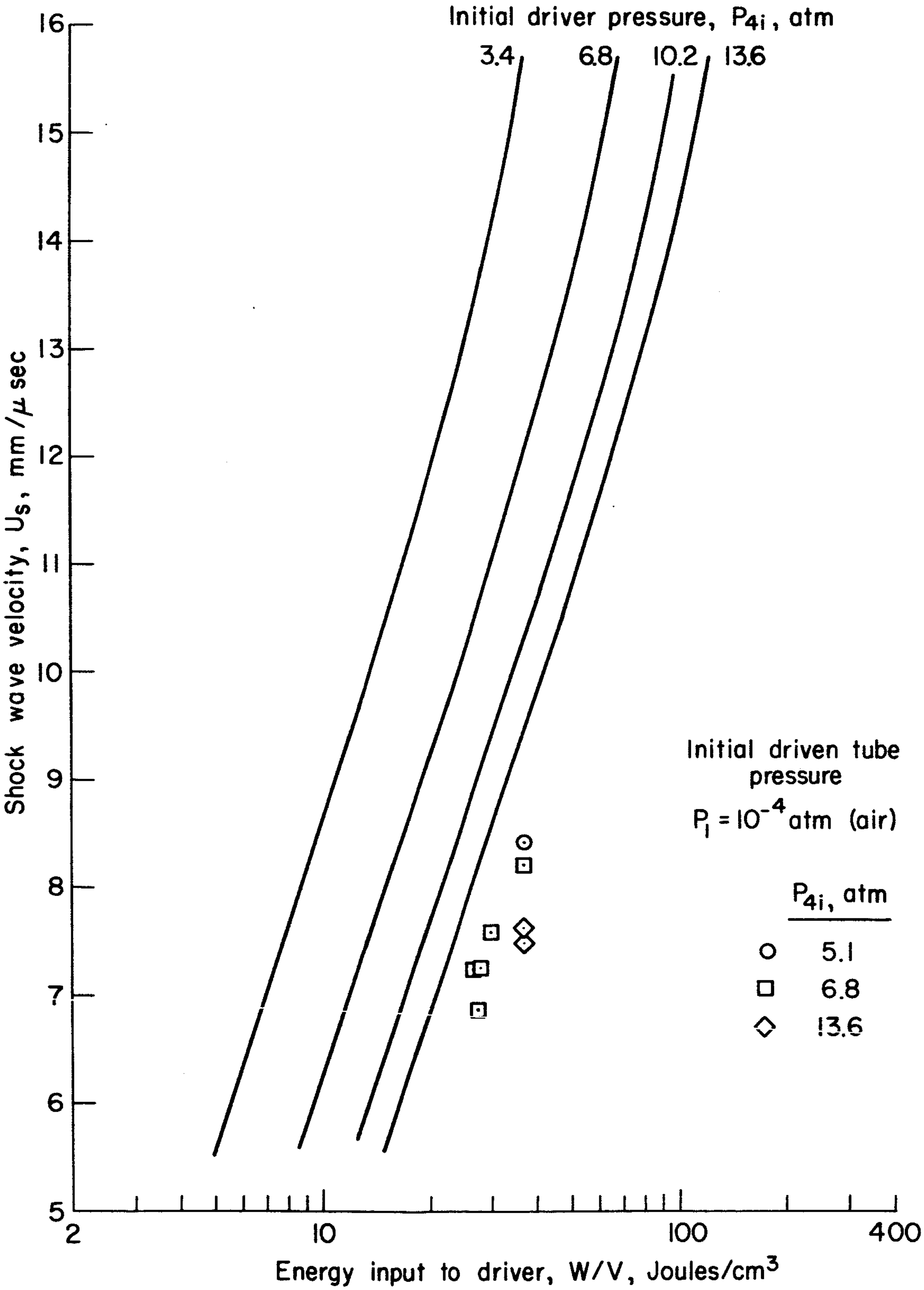
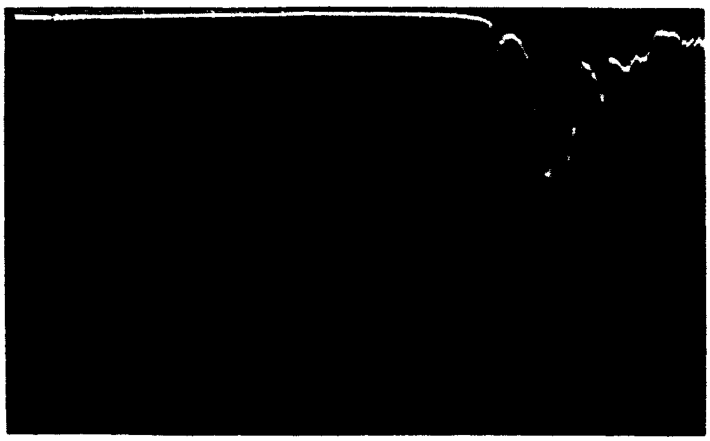


Fig. 11.- Theoretical and actual shock wave velocities as a function of energy input to driver and initial driven charging pressure.

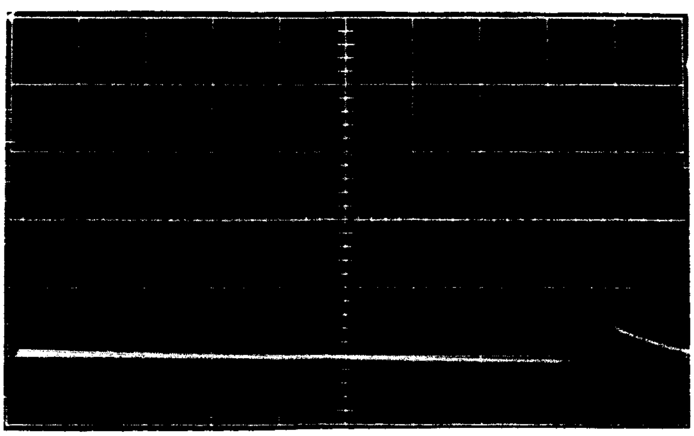
50 μsec/cm

(a) Photomultiplier output at an initial driven tube pressure of 10^{-4} atm and a shock velocity of 8.1 km/sec.



50 μsec/cm

(b) Photomultiplier output at an initial driven tube pressure of 3×10^{-4} atm and a shock velocity of approximately 7 km/sec.



20 μsec/cm

(c) Ionization gage output at an initial pressure of 10^{-4} atm and a shock velocity of 7.1 km/sec.

Fig. 12.- Oscilloscope traces for shock velocity measurements.

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Driver pressure

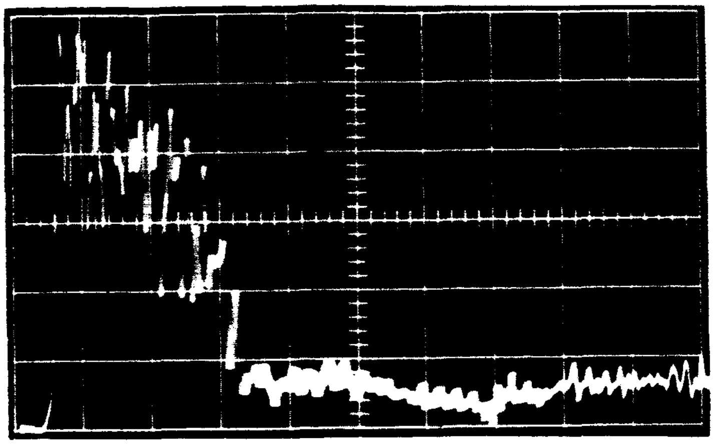

Fig. 13.- Oscilloscope record of transducer output measuring driver pressure. Initial driver charging pressure is 13.6 atm. Ideal maximum pressure based on 100 percent efficiency is 226 atm. Output has been filtered with a 50 kc filter (500 psi/cm = 34 atm/cm).

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